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Göhler, Simon Moritz; Howard, Thomas J.

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A Framework for the Application of Robust Design Methods and Tools

S. M. Göhler, T. J. Howard
Technical University of Denmark

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Abstract

Robust Design (RD) Methods have become a powerful concept to design more reliable products. However, there is still confusion and doubts in the industry about the use and effectiveness of these methods. Mostly the problems experienced in industry are related to a poor application or knowledge of the methods by the companies. Expectations to the output are sometimes misleading and imply the incorrect utilization of tools. A framework for the application of tools and methods typically associated with Robust Design Methodology (RDM) in the literature is provided in this paper. It is proposed to organize the tools and methods by means of a faceted classification in terms of their purpose and premise. An example is used to illustrate the differences of the facets. This framework clarifies the underlying premises of RD tools for professionals working with design processes and can serve as guidance for an organization on how to structure its development process and how to make most efficient use of the existing tools.

1. Introduction

The idea of Robust Design is to reduce a design's sensitivity to variation and noise factors. Generally, these can be categorized as manufacturing and assembly variations, load deformations, variation due to ambient conditions and variation over time (Ebro et al., 2012). Arvidsson and Gremyr (2008) summarized the principles of robust design methodology as awareness of variation, insensitivity to noise factors, application of various methods and application in all stages of a design process. They defined Robust Design Methodology as "systematic efforts to achieve insensitivity to noise factors" (Arvidsson and Gremyr, 2008). Robust Design Methodology (RDM) has a long tradition since Quality Engineering pioneer Taguchi first started to promote the principles in the 1950s adapting the signal to noise ratio from communication systems. RDM spread firstly over Japan and then to Western industries, mainly US companies in the 1980s (Wu and Wu, 2000). However, studies conducted in companies in Sweden, UK and the USA (Gremyr et al., 2003), (Araujo et al., 1996), (Thornton et al., 2000) showed that the application of RDM in industry is poor. The lack of knowledge regarding the general idea of RD and the potential benefits were among the identified reasons. It has also been shown that even among companies considered to be mature in the field of robust design, the practices and processes are quite different with no single framework or process (Krogstie et al., 2014).
A literature study on the topic of Robust Design reveals a lot of different methods, techniques, tools, principles, frameworks and visualizations with the goal of improving the design to be less sensitive to variation. The complexity ranges from simple design rules to sophisticated

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time-consuming computer simulations and optimizations. Previous literature reviews and classifications for RDM tools had various foci. Eifler et al (2013) focused on the phase of application of RDM tools in the development process and if they are lagging or leading methods. Park et al (2006) classified methods in three coarse categories of i) Taguchi Method, ii) Robust Optimization and iii) Axiomatic approach and reviewed the state of the art in these areas. Other reviews focused on Robust Parameter Design (Robinson et al, 2004) or on practices to address the principles of RDM as defined by Arvidsson and Gremyr (Hasenkamp et al, 2009). However, due to the different foci of the mentioned reviews and classifications, the issue of poor understanding and application of RD tools is not addressed. The authors believe that understanding the premises rather than attributes of the methods supports the correct and successful application. This paper makes an attempt to create a framework for the application of tools and methods typically related to Robust Design in the literature by means of a faceted classification. The goal is to increase the understanding and provide support for the application of RD methods. The proposed facets are (i) Robust Design Guidance and Principles, (ii) Robustness Evaluation, (iii) Robustness Optimization and (iv) Robustness Visualization. The framework aims at professionals working with design processes to increase the awareness of premises and goals of methods. It can serve as guidance for structuring the development process. Further, this framework could be of interest for researchers from the field of design processes to derive a generic landscape for RDM built upon the main premises and goals of each method.

The outline of the paper is as follows. Firstly, Robust Design is delimited from related fields. Secondly, a framework for RD methods and tools is proposed by means of a faceted classification. Thirdly, selected methods and tools are reviewed and described to support the framework. An example is presented to show the nature of the individual facets. Finally, the findings are discussed and conclusions drawn.

2. Delimitation of Robust Design

In the following section the criteria for the selection of tools and methods being reviewed and used for creating the framework will be described. Generally, a distinction between Robust Design and related areas and frameworks such as Reliability Engineering, Risk Management and approaches such as Design for Assembly, Manufacturing or Six Sigma is necessary. This however is not always clear since mentioned areas are interlinked and overlap occasionally.

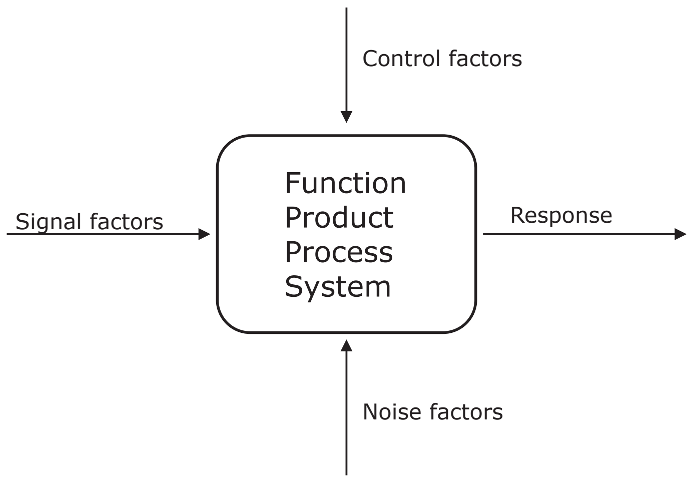

Figure 1. Generic P-Diagram

Robust Design provides the framework for the development of designs and products insensitive to variation and for the assessment of the sensitivity of functions to variation. Variation in this context could be in terms of control factors i.e. design parameters but also uncontrollable noise factors like environment, usage etc. Figure 1 shows a generic P-diagram visualizing the input and output – i.e. Signal and Response factors - as well as control and noise factors to a function, product, process or system.

Methods from related fields like Reliability Engineering and Risk Management, Design for X, Design for Manufacture and Assembly **which are not aiming at understanding or reduction of sensitivity to variation** have not been taken into account for this study. Complexity Management and Systems Engineering also have overlaps with Robust Design but will not be discussed as such in this work. Further, management frameworks such as Variation Risk Management (Thornton, 2004) are not part of this study.

3. Faceted Classification of Robust Design tools

The following section proposes a new framework for the application of methods and tools related to RD by organizing them by means of faceted classification. The methodology used to derive the facets is described. As mentioned above, there have been previous attempts to classify RD tools and methods. The review from different angles and with different goals led to the fact that there are methods that occur in one review but not in the others. For this study methods that are commonly associated with RD as delimited in Section 2 have been collected from other review papers in this field. Additionally, the authors augmented the list with some methods based on their experiences in product development. Table 1 lists the methods and tools related to RD that have been selected.

Table 1. List of reviewed RD tools and methods

1	Axiomatic Design
2	Design Clarity
3	Design Matrix
4	Design Principles
5	Design of Experience (DoE)
6	Kinematic Design
7	Locating Scheme
8	Monte-Carlo-Analysis
9	P-Diagram
10	Taguchi Method
11	Physical Decomposition of Functions
12	Ishikava / Fishbone Diagram
13	Quality Loss Functions
14	Quality Function Deployment (QFD) / House of Quality
15	Sensitivity Studies
16	Transfer Functions
17	Tolerance Management
18	Variation Mode and Effect Analysis (VMEA)
19	Response Surface Methodology

After the selection of the commonly used RD tools, the literature has been reviewed to find the main premise of each of the methods and tools. Four main premises of application have been found and used as facets to classify the reviewed methods and tools.

1. Robust Design Guidance and Principles
2. Robustness Evaluation
3. Robustness Optimization
4. Robustness Visualization

The description of the associated methods and an example case is used to elaborate the reasoning of and the differences between the facets. Tools and methods do not necessarily need to be bound to one facet but can have multiple purposes and benefits. For detailed descriptions of the methods, the authors recommend the review of cited references or other available books and publications.

3.1 Example introduction

The design of a sled for the laser in a DVD player was chosen as an example to illustrate the premise of each facet by applying a related method. For simplicity reasons only two requirements shall be considered: firstly, the force required to drive the sled for the selection of an appropriate motor and secondly, the position accuracy of the laser. Generally speaking these functions can be described as follows:

1. Sled driving force = f(mass, materials, lubrication, play of sled on rails)
2. Laser position = f(rail positions, play of sled on rails)

The sled driving force is a function of mass that needs to be accelerated and the friction on the rail. Let's assume the weight and the material of the sled as well as the lubrication are fixed and not part of the design space. That leaves the play for the connection between sled and rail and the resulting friction losses for the whole operating distance as main contributor to the required driving force. Secondly, the positioning of the laser on the sled in the horizontal plane is of interest. Figure 2 shows two proposed concepts in a principle sketch. The example will be used to illustrate the proposed facets by applying some of the RDM tools associated with them.

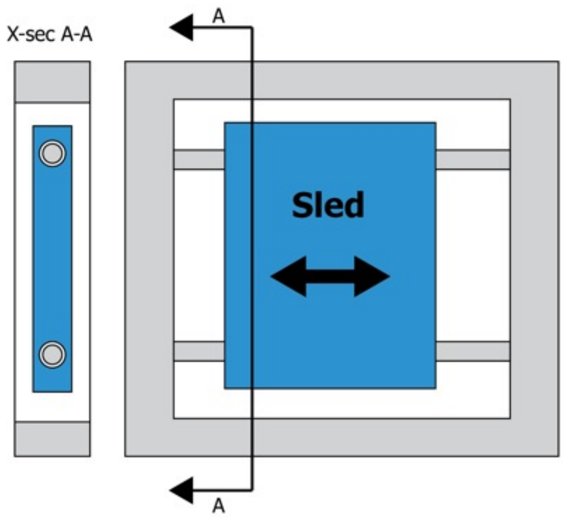

Figure 2a. Design Concept A for DVD player sled

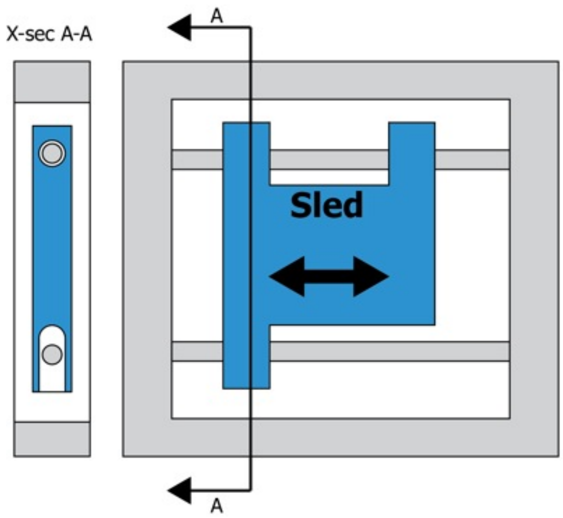

Figure 2b. Design Concept B for DVD player sled

3.2 Robust Design Guidance and Principles

Axiomatic Design was firstly proposed by Suh (2001). In his approach he argues that basic robustness against variation builds upon two basic principles i.e. axioms. Firstly, the independence axiom stating that functions should not be coupled, and secondly, the information axiom which can be reduced to the principle to design functions as simple as possible not having unnecessarily many design parameters that influence a function. In summary the idea is to un- or decouple all functions from each other to get independent functions that are adjustable by a set of design parameters that do not interfere with other functions. *Physical Decomposition of Functions* is a way of utilizing the concept of *Axiomatic Design* and maintaining the independence of functions. Andersson (1996) argues that different concepts have different optimums and that considering Design Principles in the concept phase leads to design solutions with a higher baseline robustness and potentially more opportunities for improvement. Matthiassen (1997) describes *Design Principles* as a “tool conveying knowledge of what tends to be good or poor design practice”. Pahl and Beitz (2007), Matthiassen (1997) and Mørup (1993) elaborate over general design rules that make the design more robust to variation but also less sensitive to failures. Examples are to avoid tolerance stack-ups (*Tolerance Management*), utilize self-adjustment, unambiguous loading and many more. Work done by Ebro and Howard follows some of these principles. *Design Clarity* and *Kinematic Design* ensure to avoid over-constraints and to create unambiguous interfaces to make to the design insensitive to variation (Ebro et al., 2012). A similar approach is proposed by Söderberg using *Locating Scheme* Methods to find and optimize the number and position of the constraints (Söderberg et al., 2006). Methods and tools in the facet of Robust Design Guidance and Principles can be applied in the sketch phase and don’t require a detailed design.

All methods and tools mentioned in this paragraph support the designer from the concept level to the final product in designing in robustness. Simple design rules and proposals from experiences in mechanical design are utilized to decrease the sensitivity to variation.

For the example design problem of the DVD laser sled, Design for Clarity and Kinematic Design can be applied in the early design stage on concept level. Figure 2a shows a design solution where the sled is fully guided on both rails. Considering nominal values and checking the Degrees of Freedom (DOF) for the sled indicates that this design would work. However, evaluating the intended and actual constrains following the Kinematic Design approach, it shows that the design is over-constrained, which could lead to high required forces to drive the sled, the mechanism jamming or excessive wear in the case of variation especially if the rails are not parallel to each other. In that case the design is also ambiguous with respect to the positioning requirement and which of the rails locates the sled in each of the directions. Using Suh’s Axiomatic Design philosophy it can be seen that both requirements (force and position) are dependent on the angle between the two rails and therefore violate the independence axiom – the functions are coupled. Figure 2b shows a sketch for the improved design following the Design for Clarity and Locating Scheme Methodology. The connection to the rails has been reduced to two bearings and a fork giving the ideal number of constraints. For this design the friction and therefore the force required to drive the sled is only dependent on the play of the bearings and decoupled from the positioning requirement.

3.3 Robustness Evaluation

To predict the robustness of products in production and service it is of high importance to evaluate the robustness during the development process. Robust Design tools for Robustness Evaluation give relative or absolute (metric) information about how sensitive to variation a design is. Per se these tools do not improve the robustness of a product but give an important input for comparisons of design solutions or even estimated yield rates and the prediction of reliability as a support in the decision making process. In an early design stage these methods build upon general attributes of the design concept that could be for example first sketches of working principles or the general composition of the design without details and return a value for the estimated level of robustness against variation. They often relate to design guidelines that have or have not been or could not be taken into account. Ebro and Howard have utilized the principles of *Design Clarity* and *Kinematic Design* to derive objective scores for over-constraints and mobility and therefore for robustness (Ebro et al., 2012). Expert experience is also utilized to evaluate a design. *Variation Mode* and *Effect Analysis* (VMEA) is - like Failure Mode and Effect Analysis (FMEA) for reliability - a tool to judge the sensitivity to variation. Whilst the values are somewhat subjective it still gives a first estimation of robustness (Johansson et al., 2006). *Transfer Functions* relate the change in design parameters to the effect on the function. In the case that a transfer function can be derived analytically (from the working principle for example), *Sensitivity Studies* can be run before the actual design has been fixed to give insights of how to design in the most robust way. The further a design solution matures the more options of predicting the robustness of the final product arise. *Taguchi's* Signal-to-Noise-Ratio can be used to evaluate the robustness. But also sensitivity scores from parameter sensitivity studies, probability distributions from *Monte-Carlo-Analyses* and tolerance chains (*Tolerance Management*) give an indication of robustness. *Design Matrices* as proposed by Suh (2001) that connect the functional requirements with the design parameters can be seen as Robustness Evaluation since the entries reflect the sensitivity of each function to the related design parameters. Once CAD models of the design are available, assessments with other advanced simulation software packages are possible, like for example Finite Element Methods (FEM), Computational Fluid Dynamics (CFD) etc. Sophisticated *Transfer Functions* and *Response Surfaces* can be derived that show functional sensitivities to variations on a detailed level. Once there is more detailed information about the design and maybe first samples from production are available, the *VMEA* can be updated and filled with objective values.

In the example design case of the DVD laser sled, engineers could be interested in evaluating the robustness with respect to the required driving force of the sled to select an appropriate motor. Deriving the Transfer Function and running a Monte-Carlo-Analysis with the expected production variation would enable them to calculate the variation and distribution of the driving force and select the motor.

3.4 Robustness Optimization

Optimization implies that a solution exists that can be improved. This solution can be optimized with respect to functional performance, durability, reliability, robustness, etc. Optimization builds upon knowledge of the system and how functions behave for changes in the design parameters. Generally speaking the optimization process can be divided into two phases. Firstly, the analysis phase where insight to the problem is gained. Where possible it is desirable to have an analytical expression to define the behavior of the system, as changes can be made quickly at early stages without excessive prototyping. However, in many real world situations there are simply too many variables and noise factors to formulate an analytical expression, so experimentation or simulation has to be conducted in order to derive an approximate one. Secondly, there is the phase of the actual optimization of the then fully formalized problem. Both phases are subject to excessive research themselves. The aim is to efficiently conduct experiments or simulations with the maximum information content and the least effort. The same applies for the optimization. Trail-and-Error and simple *Sensitivity Studies* (change of one parameter at a time) are the most obvious and intuitive approaches and still used for Robustness Optimization in industry. Also experience plays an important role in this context. For design problems where *Transfer Functions* can be derived, an optimization of the design parameters can be run to find the most robust solution. For problems with higher complexities i.e. as the number of design parameters and functional requirements increase, the number of necessary experiments or simulations rises exponentially. The need for a structured experimental design arises to keep the amount of testing and simulations as low as possible.

The first work on Experimental Design was conducted by R. A. Fisher in the 1920s ("The Arrangement of Field Experiments" (1926) and "The Design of Experiments (1935)) (Antony, 2003). Since then Design of Experiment (DoE) has been developed further, ranging from Orthogonal Arrays to Combined Arrays proposed by Welch (1990), *Response Surface Methodology* by Box and Wilson (1951) and many more. The approach of designing a system, optimizing it and finally managing the tolerances in the light of a design that is insensitive to variation was firstly developed by Taguchi, quality consultant and pioneer of Robust Design, in the 1950s (Wu and Wu, 2000). He divided the development process in System Design, Parameter Design and Tolerance Design covering creation, optimization and tuning in terms of quality and cost respectively (*Taguchi Method*). In the optimization phase Taguchi utilized Orthogonal Arrays for conducting efficient experiments and tests. With the data gained from these experiments it was possible to maximize the Signal-to-Noise-Ratio (SN-Ratio) and optimize the tolerances (*Tolerance Management*) for the most robust design. Taguchi used the SN-ratio to solve the optimization problem but there are numerous methods and algorithms to do so which form their own field of study. The complexity of the optimization techniques to derive the optimum rises with the amount of information drawn from testing. Taguchi's work has triggered also critics and improvements. The most recent achievements have been summarized by Robinson (Robinson et al., 2004) following among other sources a panel discussion summarized by Nair (Nair, 1992).

When designing the dimensions of the sled in the DVD player example, the play and tolerances around the holes need to be taken into account. Usually there is a design envelope within which the dimensions can be adjusted. A robustness optimization will find a combination of design parameters so that minor variations have less effect on the two main functional requirements, sled driving force and laser positioning.

3.5 Robustness Visualization

Robustness Visualization refers to tools for instance figures, diagrams or matrices that help increasing the awareness of robustness to variation without improving or quantifying the robustness of the design. The *House of Quality in QFD* is used to integrate marketing, engineering and manufacturing and link customer requirements through to manufacturing (Hauser, Clausing, 1988). The "roof" in the house of quality visualizes potential couplings and contradictions of engineering requirements that could potentially lead to robustness issues and gives a relative indication without returning a score for robustness. The *Ishikava* or *Fishbone Diagram* developed by Japanese engineer Ishikava visualizes the causes and influencing factors that affect a problem. The general categories are Equipment, Process, People, Materials, Environment and Management. In the light of robust design, noise factors can be mapped and an overview drawn of how many and which noise factors need to be taken into account without quantifying them. The *P-Diagram* shows the product, process or function with its input and output parameters but also including control and noise factors to visualize potential robustness issues and adjustment possibilities. Taguchi's *Quality Loss Function* is another way of visualizing the robustness of a function with respect to the quality perceived by the customer or user.

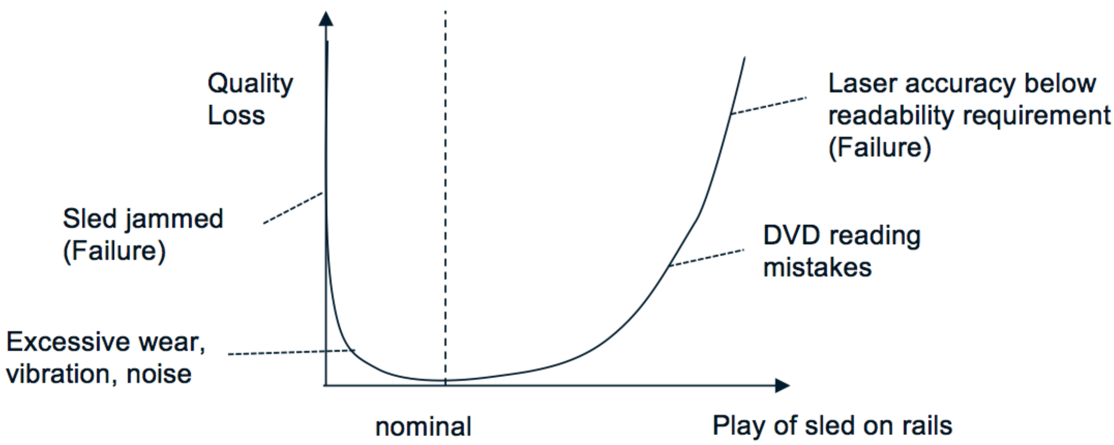

Figure 3. Quality Loss Function for example design case

Figure 3 visualizes the quality loss associated with a variation in play of the sled on the rails in the DVD player example case. For small deviations from the nominal there is no quality loss for the customer. For too little play of the sled or interference with the rail, the risk of excessive wear, vibrations and noise as well as jamming the mechanism rises. For the sled being too lose on the rails the positioning accuracy and therefore the ability to read the DVD drops from single playback mistakes to a function failure.

4. Discussion

A framework for the application of methods and tools commonly associated with RD has been proposed in this paper by means of faceted classification. The proposed facets are (i) Robust Design Guidance and Principles, (ii) Robustness Evaluation, (iii) Robustness Optimization and (iv) Robustness Visualization. Table 2 gives a summary of the faceted classification of the RD methods and tools that have been reviewed in this paper. It can be seen that some methods have more than one facet. Some tools for Robust Evaluation are also being used in the optimization process to check the result of each iteration or build upon design principles. The evaluation methods marked with a star indicate applicability in an early design stage. Tools related to Robustness Visualization can be utilized to illustrate and present robustness correlations. Most important after all, visualizations can help building up awareness of sensitivity to variation of the design and is in that respect very valuable.

Table 2. Summary of Faceted Classification of RD Methods

		Robust Design Guidance and Principles	Robust Design Evaluation	Robustness Optimization	Robustness Visualization
1	Axiomatic Design	X			
2	Design Clarity	X	X*		
3	Design Matrix		X		
4	Design Principles	X			
5	Design of Experience (DoE)			X	
6	Kinematic Design	X	X*		
7	Locating Scheme	X			
8	Monte-Carlo-Analysis		X		
9	P-Diagram				X
10	Taguchi Method		X	X	
11	Physical Decomposition of Functions	X			
12	Ishikava / Fishbone Diagram				X
13	Quality Loss Functions				X
14	Quality Function Deployment (QFD) / House of Quality				X
15	Sensitivity Studies		X	X	
16	Transfer Functions		X*	X	
17	Tolerance Management	X	X	X	
18	Variation Mode and Effect Analysis (VMEA)		X		
19	Response Surface Methodology		X	X	

X Robust Evaluation in early design stage*

Previous publications proposed different classifications of Robust Design tools and methods. Park et Al (2006) classified RD tools in three types of methods: i) Taguchi Method, ii) Robust

Optimization and iii) Robust Design with the Axiomatic Approach. In contrast to this paper, RD philosophies were discussed rather than the actual methods. Taguchi's approach is considered as its own method although significant overlaps to the second category, Robust Optimization, exist, as for example the optimization nature of parameter design. Eifler et Al (2013) reviewed RD methods and tools in the light of 3 success criteria for implementation in industry: i) leading indication of robustness, ii) quantifiable metrics and iii) early design applicability. Different to the classification proposed in this paper the premise of each method was not taken into account. Hasenkamp et Al (2009) addressed the same problem as discussed in this paper stating that "applying a tool without being aware of its underlying and motivating practice may easily lead to incorrect or suboptimal application". To overcome this shortcoming they used the principles of RDM i) insensitivity to noise factors, ii) awareness of variation and iii) continuous applicability as proposed by (Arvidsson, Gremyr, 2008) to put the tools and methods into perspective. In agreement with the reviews conducted by Eifler et Al (2013) and Hasenkamp et Al (2009) the literature study for this paper also gave the impression that the majority of contributions in this field focus on statistical and optimization oriented RD methods. Tools and methods for the evaluation of robustness in an early design stage are comparably seldom subject of investigations.

After all, the presented framework has a different goal and focus than the other reviews. It gives designers and engineers the overview of what tools and methods are available and what are the underlying premises. That eases the choice of the appropriate RD method and gives an idea of what output to expect. A weakness of this framework is the ambiguity for some methods that have multiple premises and goals.

5. Conclusion

There are many different ways of classifying methods for robust design. The aim for the approach taken in this paper was to classify tools and methods with respect to their purposes and premises to increase the understanding and give guidance for the application of RD methods. With this framework as starting point it could also be possible in the next step to specify what the input and output parameters to each tool or method are to derive a structured approach to integrate these tools into a generic development process. Weaknesses and strengths of each tool could be augmented with the overall goal of an efficient use of the existing tools.

The classification of the tools and methods of the RDM also shows a lack of options for Robustness Evaluation in early design. Furthermore, the literature study has shown approaches to combine different tools and methods. The proposed classification can help to identify overlaps as well as differences between methods and finally lead to successful integrations and combinations of tools.

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Simon Moritz Göhler, Dipl.-Ing. (MSc)
PhD Candidate
Technical University of Denmark
Department of Mechanical Engineering
Produktionstorvet Building 426, 2800 Kgs. Lyngby, DK
Tel: +45 52222612
E-mail: simogo@mek.dtu.dk
URL: www.mek.dtu.dk